MAT-90-08

Cathodic Protection of Concrete Highway Bridges

Ontario

Ministry of Transportation

Research and Development Branch

90-04591/

Technical Report Documentation Page

Cathodic Protection of Concrete Highway Bridges

Author(s):	D. G. Manning
Number:	MAT-90-08
Date of Publication:	March 1990
Published by:	Research & Development Branch, MTO
Ministry Contact:	D. G. Manning (416) 235-4688
Abstract:	The paper presents an overview of the cathodic protection of concrete highway bridges with particular reference to the work of the Ontario Ministry of Transportation. The scope includes both bridge decks and substructure components as well as the implications of applying cathodic protection to prestressed concrete members. Results of research studies and operational experience with cathodic protection over a fifteen year period are summarized. The principles of cathodic protection, the materials and components which are used and protection criteria to ensure that corrosion is arrested are described. The need for a monitoring system to ensure effective long-term operation is emphasized and future research activities identified.
Comments:	Paper prepared for the Third International Symposium on Corrosion of Reinforcement in Concrete Construction, Warwickshire, England, May 21-24, 1990. The paper was formatted to satisfy the requirements of the conference for camera-ready copy. It is reproduced in this report in the same format.
Key Words:	Anodes, bridges, cathodic protection, concrete, corrosion, protection criteria rectifiers, reference cells
Distribution:	MTO Head Office, Regions and Districts. Others on request.
Copyright Status:	Crown copyright © 1990 Ministry of Transportation

MAT-90-08

Cathodic Protection of Concrete Highway Bridges

D. G. Manning
Principal Research Engineer
Research & Development Branch, MTO

Published by
The Research and Development Branch
Ontario Ministry of Transportation
Hon. W. Wrye, Minister
P. Jacobsen, Deputy Minister

Published without prejudice as to the application of the findings.
Crown copyright reserved; however, this document may be reproduced for non-commercial purposes with attribution to the Ministry.

For additional copies, contact:
The Editor, Technical Publications
Room 320, Central Building
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8

Telephone: (416) 235-3480
Fax: (416) 235-4872

March 1990

Table of Contents

Abstract 1
Introduction 1
Principles of Cathodic Protection 2
Components and Configuration of Cathodic Protection Systems 2
Continuous Surface Anodes 3
Discrete Anodes 5
Mesh Anodes 5
Power Sources 6
Monitoring 6
Protection Criteria 8
Prestressed Concrete Bridges 8
Concluding Remarks 10
References 11

List of Tables

1/ Relative Attributes of Anode Systems 4
2/ Features of Control Modes Used for Rectifiers 7
3/ Cathodic Protection Criteria 9

CATHODIC PROTECTION OF CONCRETE HIGHWAY BRIDGES

D.G. MANNING
Research and Development Branch
Ontario Ministry of Transportation
1201 Wilson Avenue, Downsview, Ontario, M3M 1J8, Canada

ABSTRACT

The paper presents an overview of the cathodic protection of concrete highway bridges with particular reference to the work of the Ontario Ministry of Transportation. The scope includes both bridge decks and substructure components as well as the implications of applying cathodic protection to prestressed concrete members. Results of research studies and operational experience with cathodic protection over a fifteen year period are summarized. The principles of cathodic protection, the materials and components which are used and protection criteria to ensure that corrosion is arrested are described. The need for a monitoring system to ensure effective long-term operation is emphasized and future research activities identified.

INTRODUCTION

The Ontario Ministry of Transportation uses several techniques to rehabilitate corrosion-damaged, concrete bridges, one of which is cathodic protection. The method of rehabilitation used on a specific structure is determined by a formal decision-making process for which the primary inputs are the existing condition and the future needs of the structure. The number of structures to which cathodic protection has been applied is relatively small, about forty in all, because of the strict selection criteria which must be satisfied [1]. However, cathodic protection is being chosen as the most appropriate solution for an increasing number of structures, particularly as the emphasis shifts from the rehabilitation of bridge decks to other components such as piers, columns, abutments, and beams. Cathodic protection is the only method of repair available which, provided it is properly monitored and maintained, can effectively control corrosion. Other repair methods, while extending service life and restoring appearance, do not arrest ongoing corrosion.

The requirement for periodic monitoring has led Ontario to use cathodic protection only as a remedial and not as a preventive technique. For new construction, passive means of corrosion protection are used.

Once the decision has been made to apply cathodic protection, there are choices to be made in terms of the type of system to be installed. Although all cathodic protection systems contain the same basic elements, the components, complexity, and cost of the completed installation can be tailored to the needs of the specific structure. In particular, most cathodic protection systems are not equally well suited to horizontal and vertical surfaces.

This paper describes the results of research studies and operational experience of the Ontario Ministry of Transportation, over a period of fifteen years, to develop and apply cathodic protection to the decks and substructures of concrete highway bridges.

PRINCIPLES OF CATHODIC PROTECTION

The principle of cathodic protection is to inhibit the corrosion reactions by causing a direct electrical current to flow to the object being protected so that all points on the surface are polarized to a potential more anodic than the most anodic point on the object. The object then becomes cathodic with respect to an external anode, hence the term cathodic protection.

Cathodic protection has been widely used to prevent corrosion in such applications as pipelines, chemical plants, and underground storage tanks. However, the application of cathodic protection to steel embedded in concrete presents three particular problems [2]:

i) Concrete has a high resistivity.
ii) Concrete is attacked by acid which may be generated at the anode.
iii) The potential of the steel must be maintained within a narrow range. If it is too positive, corrosion can occur; if it is too negative, the concrete around the reinforcing steel may deteriorate, anode life is shortened, and hydrogen may be evolved at the cathode.

The key to the successful cathodic protection of steel in concrete is to maintain a uniform potential distribution on the steel with a minimum of applied current. This means that the resistance between the external anodes and the reinforcement must be uniform and low and that the anodes should be as large as possible to minimize the current density on both the anode and the concrete surface. In addition to satisfying the requirements dictated by the properties of the steel and concrete, the cathodic protection system must be reliable, capable of operation continuously throughout all seasons of the year and, perhaps most importantly, all its components must be durable.

The two methods of applying the current to the concrete are through the use of galvanic anodes or an impressed current source. Although studies have indicated that galvanic cathodic protection systems are possible [3], the experience in Ontario has been that there is insufficient power output to protect the steel adequately [4]. Consequently, except for research investigations, only impressed current systems have been installed.

Components and Configuration of Cathodic Protection Systems

An impressed current cathodic protection system for highway bridges consists of only a few basic components:

i) The protected metal, which is the reinforcing steel. It is essential that the protected metal be electrically continuous but, because of the way highway bridges are constructed, this requirement has been satisfied by all structures investigated in Ontario to date.
ii) An electrolyte, which is the moist concrete.
iii) Anodes placed in or on the concrete surface to provide a means of distributing electrical current to all areas of the structure to be protected.
iv) A power source, usually a transformer-rectifier, connected by electrical wiring to the anodes (positive terminal) and the reinforcing steel (negative terminal).
v) Evaluation and control devices (such as reference cells and probes) to monitor, and sometimes control, the output received at the reinforcing steel from the power source.

Much of the work in developing cathodic protection systems for bridges has, of necessity, concentrated on the anode materials, since anodes used in other fields were not well-suited to this application. Sometimes, more than one anode is used, in which case the anode connected to the power source is referred to as the primary anode and the anode in contact with the concrete as the secondary anode.

It is convenient to recognize three generic types of anode systems [5]:
i) continuous surface anodes
ii) discrete anodes
iii) mesh anodes

A summary of the relative attributes of each type of anode is given in Table 1.

Continuous Surface Anodes: The first application of cathodic protection to a bridge deck, which was in California in 1973 [6], used a conductive surface anode consisting of primary anodes of high-silicon cast iron embedded in a conductive overlay consisting of a mixture of asphalt cement and metallurgical coke breeze. This design was adopted by Ontario for installations in 1974 and 1975 [7] and subsequently modified by recessing the hardware in the deck surface and modifying the composition of the conductive overlay to produce a mixture having physical properties similar to conventional bituminous concrete [2]. The conductive overlay is protected by a conventional bituminous surface course. In 1978, the modified design was adopted as one of three standard operational procedures (the other two being installation of a waterproofing membrane or a concrete overlay) for the rehabilitation of bridge decks. The system has been installed on a small number of bridge decks each year and has a good performance history. Its use has been restricted because the conductive overlay is porous and increases the susceptibility of the concrete in the deck to freeze-thaw damage. Since air entrainment was not widely used in Ontario until about 1958, and older bridges dominate the rehabilitation program, this has limited the number of applications.

Thinner conductive coatings have also been used and the concept is well suited for vertical applications and non-trafficked areas. These include paints made conductive by the addition of carbon or graphite. Being black in colour, they have often been followed by a coat of latex paint to provide some protection against weathering and improve the appearance of the completed installation. Paints offer the advantages of

TABLE 1
Relative Attributes of Anode systems (adapted from References 5,8)

TYPE	ADVANTAGES	DISADVANTAGES
CONTINUOUS SURFACE a) Conductive Bituminous Overlay	Good current distribution. Low resistivity. Good performance history. Secondary anode dissipates gases.	Suitable only for decks. Additional dead load. Increases severity of concrete exposure.
b) Conductive Coatings i) paints	Easy to apply and repair. Good current distribution. Many coatings available. Continues to function with localized damage. Inexpensive.	Not durable in harsher environments. Sensitive to application conditions. Large seasonal variation in circuit resistance. Suitable only for low current densities. Unattractive (unless overcoated). Not suitable for wearing surfaces.
ii) flame-sprayed zinc	Good bond to concrete. Good current distribution. Appearance similar to concrete. Applicable to horizontal and vertical surfaces.	Labour-intensive application. Potential health hazard. Difficulties in quality control. Service life uncertain.
DISCRETE ANODES a) Without Overlays	Simple to install. Surface profile unchanged. Concrete surface accessible. Applicable to vertical and (if recessed) horizontal surfaces. Inexpensive.	Non-uniform current density. High current density at anode-concrete interface. Anode exposed to weather, traffic (on decks), and vandalism. Anode may touch rebar in recessed installations. Long term durability questionable.
b) With Non-Conductive Overlays	Appearance improved and anodes protected. Reduced seasonal effects. Applicable to horizontal and vertical surfaces. Acceptable appearance.	Non-uniform current density. High current density at anode-concrete interface. Anode and concrete thermally incompatible.
MESH ANODES WITH CEMENTITIOUS OVERLAY	Good current distribution. High level of redundancy. Rugged components. Acceptable appearance. Applicable to horizontal and vertical surfaces.	Damaged areas not easily repaired. Concerns with overlay durability. Limited field experience. Expensive.

ease of installation and repair, and low cost, but have failed to exhibit sufficient durability in the outdoor environment, often lasting for no more than two years under Ontario conditions.

By contrast, a single installation of a surface coating of flame-sprayed zinc (used as the anode in an impressed current system) has performed well over a period of 5 years. The application was slow and problems were experienced in activating the installation because of short circuits [9]. These difficulties, combined with the relatively high costs, caused the zinc coating to be viewed with disfavour. However, the system has protected the steel against corrosion, there has been no apparent deterioration of the zinc, and the appearance is unobtrusive. Further, the costs, when compared with systems installed since 1984 rather than with the paints which subsequently failed, no longer appear excessive and this is resulting in further consideration of flame-sprayed zinc. The method of application, the optimum coating thickness, and long-term performance are the major topics requiring further investigation.

Discrete Anodes: The second generic type of anode system consists of discrete anodes placed on or recessed in the concrete surface, with or without the protection of a cementitious overlay. Anodes of this type used in Ontario have included platinized wires placed in slots cut in the concrete surface and filled with grout [10]. The installation was unsuccessful because of uneven current distribution to the steel and acid attack on the grout surrounding the anode. Conductive polymer rods made from a vinyl ester and metallurgical coke were used in conjunction with a conventional shotcrete overcoat on a vertical surface in a 1982 Ontario trial [11]. The system was generally satisfactory from the electrical standpoint, but failed because of debonding of the shotcrete. The same polymer has been widely used on bridge decks in the United States, placed either on a horizontal surface in mounded strips and overlaid with concrete or in slots sawn in the deck surface. Slot systems have the advantages of low cost and not requiring other modifications to the deck such as raising the expansion joints. Their performance has however, been poor because of non-uniform current distribution which increases as the distance between the anodes increases, high current densities on the small anodes, and the difficulties of avoiding contact with the reinforcing steel during installation because a common feature of decks which are exhibiting corrosion damage is low cover to the reinforcement. The installations are also vulnerable to damage from vehicular traffic and weathering, particularly following the development of a crack between the anode and the concrete as a result of the different expansion characteristics of the two materials. The mounded installations have generally performed better but the costs are much higher and there has been cracking of the overlay because of the thermal incompatibility between the polymer anode and the concrete overlay. A further example of use of discrete anodes has been the surface-mounted ceramic anodes installed on substructures in the United Kingdom.

Mesh Anodes: The third generic group is the mesh anodes consisting of a grid of anode material, usually embedded in a cementitious overlay. Conductive polymer and carbon fibre meshes embedded in shotcrete were included in the Ontario trials on substructure components, but failed because of debonding of the shotcrete [9]. In 1985, the first trial of a metal oxide-coated titanium was installed on a bridge column. This was

followed by a permanent installation on a large pier using normal bidding procedures in 1986 and the award of a contract for the installation of 6700 m² on bridge piers in 1989. A trial installation was conducted in 1988 on a bridge deck in which the mesh was embedded in a concrete overlay. The major objective was to determine whether this configuration was feasible and would be suitable for future applications to bridges where the air-void system in the concrete is inadequate, or to post-tensioned thick slab decks where it is necessary to cathodically protect the top mat of reinforcement and also prevent further ingress of chloride ions to the much deeper post- tensioned steel. The installation also afforded the opportunity to evaluate titanium mesh anodes from two different sources [12].

The major factors which affect the choice of anode material and configuration are whether the installation is on a vertical or horizontal surface, the condition of the concrete and the extent of repair required, the air-void system parameters, and depth of cover to the reinforcing steel. Other factors such as vulnerability of the installation to vandalism and the appearance of the completed installation may be serious concerns in some locations.

POWER SOURCES

Most cathodic protection installations are powered by a transformer-rectifier. These units, available from several commercial sources take 110 V, AC line power, reduce its voltage and convert it to a direct current (DC) waveform. The typical rectifier used for bridge deck installations has maximum voltage and current outputs of 8 volts and 4 amps respectively. Most systems operate with voltages and currents considerably below the maximum values.

There are three basic methods of controlling the output of transformer-rectifiers viz. constant current, constant voltage, or constant potential control. More sophisticated rectifiers offer all three modes of operation. Constant current output is the most widely used. The relative merits of the three methods of rectifier operation are summarized in Table 2.

Some structures may be located at sites where AC line power is not available. In such cases, a storage battery, either alone or in combination with a wind or solar powered generator, can be considered. Each alternative is far from ideal. Storage batteries used alone require regular recharging; solar panels are expensive and are vulnerable to vandalism and theft; small scale wind turbines are expensive, inefficient, and their long-term reliability is questionable.

MONITORING

To be effective, cathodic protection systems must be the subject of regular monitoring, followed by appropriate intervention if the measurements recorded are outside prescribed limits. Monitoring includes measurement of the output from the power source, the polarization of the reinforcement, and an assessment of the condition of components of the system.

TABLE 2
Features of Control Modes Used For Rectifiers

MODE	DESCRIPTION	ADVANTAGE
CONSTANT CURRENT	. Rectifier maintains a constant current output. . Voltage varies with changes in circuit resistance. . Steel potential may be monitored independently.	Protection current predicted by an E-log I test, or determined from past experience on similar structures, can be set and maintained.
CONSTANT VOLTAGE	. Rectifier maintains a constant voltage output. . Current varies with change in circuit resistance. . Steel potential may be monitored independently.	Current flow is greatest when corrosion is most likely to occur, i.e. when concrete resistance is lowest. (Voltage level must be selected with care.)
CONSTANT POTENTIAL	. Steel potential, measured by a permanently embedded reference electrode, is input to the rectifier. . Sufficient current/voltage is supplied to maintain a pre-selected "protection" potential level. . Rectifier must be capable of measuring IR drop free values.	Adherence to the specified criterion is assured providing each reference cell used for control remains stable and accurate over the long term, and is representative of conditions in the zone.

The polarization of the reinforcement can be measured using surface techniques or embedded instrumentation. Surface techniques, such as portable half-cell potential surveys or polarization testing, have the advantages of simplicity and reliability, but are time-consuming and require access to the concrete surface. Access may be limited by the type of anode, by traffic in the case of decks, or by height or site conditions in the case of substructure installations. Embedded monitoring devices, installed at the time of construction of the cathodic protection system, are therefore very desirable. Embedded instrumentation, especially reference cells suitable for use in concrete, has been the subject of considerable study [11,13,14]. Graphite electrodes have been found to be the most suitable under field conditions in Ontario. Other types of cells, including several commercial cells, were found to be unstable with respect to either time, sub-freezing temperatures, or the chloride content of the concrete. Graphite electrodes are now included in all cathodic protection installations by the Ministry, although the evaluation of other types of reference cell continues.

Commercial rate-of-corrosion probes have been used, with varying degrees of success, to monitor the effectiveness of cathodic protection in stopping corrosion. "Macrocells", which are strong, natural corrosion cells comprising steel in concrete to which salt has been added intentionally, can also be used to measure whether corrosion activity is halted. It was found [13] that these cells experienced irreversible

potential shifts with time and were most useful for monitoring effects during activation of an installation. Embedded steel probes have also been used effectively to measure the distribution of current in cathodic protection systems.

In addition to taking measurements via embedded instrumentation, the voltage and current output from the rectifier must be monitored. Regularly scheduled visits by trained personnel help ensure constant and effective operation of cathodic protection systems. During such visits, the physical condition of the system components should be checked as far as it is possible for evidence of deterioration and for acts of vandalism or lightning strikes, which are not uncommon.

The use of computer-driven monitoring systems, utilizing telephone hook-ups, offer a means of improving the regularity of measurements and allowing a rapid response to correct faults or make adjustments to satisfy limit conditions. These systems have been used successfully and, while they reduce the need for site visits, they do not eliminate them.

PROTECTION CRITERIA

One of the most controversial aspects of the cathodic protection of steel embedded in concrete is the method to be used to determine whether sufficient current is being applied to the structure to halt the corrosion of the steel. Since this cannot be measured directly, various criteria have been proposed [15]. The first criteria suggested were based on criteria used in the pipeline industry and, while it is generally agreed that these are too conservative when applied to steel in concrete, there is little unanimity on the criterion which should be used. The more common criteria which have been suggested are summarized in Table 3.

The Ontario Ministry of Transportation has adopted the 100 mV potential shift criterion, based on a four hour period of depolarization. The validity of the criterion, which is typically satisfied at current densities of approximately 10 mA/m^2 of reinforcing steel surface, has been supported by measurements taken on rate-of-corrosion probes, macrocells, and current pick-up probes in a variety of structures. However, it is recognized that, as with the other criteria, there are unresolved questions. These involve not only the particular values of potential shift and time selected, but also the fact that the rate of depolarization can differ widely from structure to structure and the results are strongly influenced by the number and location of readings on the structure.

In recognition of the limitations and uncertainty involving the adequacy of protection criteria, in 1988 the Ministry initiated a long-term, outdoor exposure plot study to examine the effects of operation under several criteria. The study is scheduled to run for at least five years.

PRESTRESSED CONCRETE BRIDGES

As the proportion of prestressed concrete structures in the bridge population increases, and the older structures begin to exhibit corrosion-induced damage, there is a growing urgency to determine whether cathodic protection can be applied safely to prestressed concrete members. There are two aspects of concern [8]:

TABLE 3
Cathodic Protection Criteria (from Reference 5)

BASIS	DESCRIPTION	COMMENTS
POTENTIAL SHIFT	1) 100 mV positive potential shift between (IR drop free) potential reading during system operation, and depolarized potential (usually after 4 hours).	. Requires only short term stability of reference cells for potential measurement. . Convenient, easily measured. . Minimal equipment required. . Time period and shift required still under debate.
	2) 300 mV negative shift in potential between static potential and (IR drop free) potential measurement, during operation.	. Requires reference cell be stable over the long term, or . May be necessary to periodically re-determine static potential (by depolarizing system). . Minimal equipment required.
POTENTIAL VALUE	Potential value of -.850 V (sometimes -.770 V is used) relative to a copper-copper sulphate reference cell.	. Convenient, easily measured. . Minimal equipment required. . Considered conservative; concern with effects of overprotection.
E-LOG I TEST	Plotting E (potential) versus I (applied current) over a range of potentials, allows calculation of required protection current.	. Structure-specific. . Test equipment is complex, requires skilled operator. . Time consuming test. . Plots sensitive to interpretation. . Conservative.
MACROCELLS, RATE-OF-CORROSION PROBES	Apply current necessary to reduce the measured corrosion current flow to zero.	. Based on direct corrosion measurement. . No guarantee probe behaviour is the same as that of the steel. . Requires embedded instrumentation. . Macrocell effectiveness relatively short term.
CURRENT DENSITY	Apply current of 10 mA/m² of reinforcing steel surface area.	. Empirical, based on limited laboratory/field experience.

i) To determine whether the application of cathodic protection to protect the mild steel reinforcement in prestressed structures may have an adverse effect on the prestressing steel.

ii) To determine whether cathodic protection can be used to protect pre-tensioned and post-tensioned members, in view of the increased risk of hydrogen embrittlement in high strength steels as the potential is shifted in the negative direction.

A laboratory study was begun in 1985 [16] on full scale deck sections, but with the prestressing steel in an unstressed condition. It was concluded that cathodically protecting the mild steel reinforcement in a thick, post-tensioned deck slab would not adversely affect the prestressing steel under normal operating conditions. However, the tendons would not be protected in a deck where the tendons and metal ducts were in electrical contact, which is the usual case. Cathodically protecting the mild steel reinforcement in thin slab decks was also judged unlikely to have any adverse effects on the girders, provided that the applied current density on the deck surface did not exceed 20 mA/m^2. The study recommended that caution be exercised in any attempt to cathodically protect the prestressing steel in pre-tensioned beams. It was found to be extremely difficult to obtain a uniform current distribution, which could leave some steel unprotected, or result in hydrogen evolution in the zones of highest current density.

Although the results of the laboratory study were generally predicable, no attempt was made to quantify the effects of potential shifts on high strength steels under stress. A further laboratory investigation was initiated in 1988 to examine the effects of applying cathodic protection to concrete containing highly-stressed steel. This study is still in progress.

CONCLUDING REMARKS

Since its first use on a bridge deck in 1973, cathodic protection has become recognized as a valid rehabilitation technique for corrosion-damaged highway bridges. The standard conductive asphalt cathodic protection system used on bridge decks in Ontario has performed well, but existing selection criteria have limited its application to only a relatively small number of bridges. Work is therefore continuing with the objective of identifying systems which will allow cathodic protection to be considered on a much wider range of bridges, particularly on older bridges and those which are badly deteriorated.

The work on substructures has demonstrated that cathodic protection is also viable. However, it has also emphasized that the selection of cathodic protection is not to be taken lightly because not all installations have performed as designed. It is necessary to develop an engineered solution for each structure based on the condition of the structure and the requirements of the owner. It is also essential, for effective long-term operation, to ensure that there will be a regularly scheduled monitoring program before a cathodic protection system is installed.

Further research on decks and substructures will continue and will concentrate on selection criteria for the use of cathodic protection; long-term effects on mild and prestressed reinforcement, the identification of the most appropriate protection criterion; and the durability of components which is of particular concern in the harsh highway environment.

REFERENCES

1. "Structure Rehabilitation Manual", Manual SO-88-7, Ontario Ministry of Transportation, (1988).

2. Manning, D.G., and Schell, H.C., "Cathodic Protection of Bridges", American Concrete Institute SP-93, pp 585-608 (1986).

3. Whiting, D., and Stark, D., "Galvanic Cathodic Protection for Reinforced Concrete Bridge Decks - Field Evaluation", NCHRP Report 234, 63 pp, (June 1981).

4. Manning, D.G., and Schell, H.C., "Early Performance of Eight Experimental Cathodic Protection Systems at the Burlington Bay Skyway Test Site", Transportation Research Record No. 1041, pp 23-32, (1985).

5. Schell, H.C., "Cathodic Protection of Concrete Bridges", Proceedings, The First Canadian Symposium on Cement and Concrete, Laval University, Quebec, no pagination, (1989).

6. Stratfull, R.F., "Experimental Cathodic Protection of a Bridge Deck", Transportation Research Record No. 500, pp 1-15, (1974).

7. Fromm, H.J., "Cathodic Protection of Rebar in Concrete Bridge Decks", Materials Performance, Vol. 16, No. 11, pp 21-29, (November 1977).

8. Manning, D.G., "Durability of Prestressed Concrete Highway Structures", NCHRP Synthesis of Highway Practice No. 140, Transportation Research Board, 65 pp (1988).

9. Manning, D.G., and Schell, H.C., "Substructure Cathodic Protection in Ontario: Field Trials 1982 to 1984", Transportation Research Record No. 1113, pp 47-53, (1987).

10. Fromm, H.J., and Pianca, F., "Evaluation of Platinized Niobium Wire Anodes for Cathodic Protection of Bridge Support Structures", Transportation Research Record No. 860, pp 40-45,)1982).

11. Manning, D.G., Clear, K.C., and Schell, H.C., "Cathodic Protection of Bridge Substructures - Burlington Bay Test Site, Design and Construction Phases", Transportation Research Record No. 962, pp 29-37, (1984).

12. Schell, H.C., and Manning, D.G., "Research Directions in Cathodic Protection for Highway Bridges - Ontario Ministry of Transportation", Paper No. 385, Corrosion 89, National Association of Corrosion Engineers (1989).

13. Schell, H.C., and Manning, D.G., "Evaluating the Performance of Cathodic Protection Systems on Reinforced Concrete Bridge Substructures", Materials Performance, Vol. 24, No. 7, pp 18-25 (1985).

14. Schell, H.C., Manning, D.G., and Pianca, F., "Reference Cells for Embedment in Cathodically Protected Concrete", to be published in the Transportation Research Record, (1989).

15. Stratfull, R.F., "Criteria for the Cathodic Protection of Bridge Decks", Corrosion of Reinforcement in Concrete Construction, A.P. Crane Ed., Ellis Horwood, pp 287-331 (1983).

16. Hope, B.B., and Ip, A.K.C., "Application of Cathodic Protection to Prestressed Concrete Bridges", Report ME-87-01, Ontario Ministry of Transportation (1987).